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Icing Research Tunnel Rotating Bar Calibration Measurement System

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ABSTRACT

To measure icing patterns across a test section of the Icing Research Tunnel, an automated rotating bar measurement system was developed at the NASA Lewis Research Center. In comparison with the previously used manual measurement system, this system provides a number of improvements: increased accuracy and repeatability, increased number of data points, reduced tunnel operating time, and improved documentation. The automated system uses a linear variable differential transformer (LVDT) to measure ice accretion. This instrument is driven along the bar by means of an intelligent stepper motor which also controls data recording. This paper describes the rotating bar calibration measurement system.

KEYWORDS

Calibration, Data Acquisition, Displacement, Sensor

INTRODUCTION

The Icing Research Tunnel at the NASA Lewis Research Center is the largest and one of the oldest refrigerated icing research tunnels in the world. This International Historical Mechanical Engineering Landmark was built to study the hazardous conditions created by ice formations on aircraft components. Although at least two other known icing tunnels existed prior to its construction, they were limited as to the type and scale of testing and experimentation.

In the early 1940's technology had advanced to a level that it became possible to develop a large icing wind tunnel. It took 2 years, 1942 to 1944, to design and construct the Icing Research Tunnel. Aside from its size, other major innovations were its heat exchangers and refrigeration system and then in the early 1950's, its spray system, which made it possible to simulate the aircraft icing environment. The refrigeration plant can achieve and maintain desired air temperatures, and the spray bar system can

generate a cloud of microscopic droplets of super-cooled water. The Icing Research Tunnel and the locations of the spray bars in the test section are shown in Figure 1 (1 and 2).

The importance of the spray bar system is that it produces a uniform cloud, which provides the researcher with a documented cloud size and aids in determining the maximum size model that can be tested in the facility. The measurement of cloud uniformity is also important in detecting changes caused by the deterioration of individual water spray nozzles (3 and R. Cubbison, "November 1987 Calibration of the NASA Lewis Research Center Icing Research Tunnel," unpublished report).

In use for many years was a manual system in which a set of nonrotating round bars was placed vertically in the test section. The tunnel was cooled down and the spray bars turned on to produce a buildup of ice. The circumference of the ice accretion on the bars was then measured manually by using a flexible tape measure at 2-in. (50.8-mm) intervals (Figure 2). From the data gathered, contour plots were made indicating the lines of constant ice accretion across the test section.

GENERAL DESCRIPTION

The iceprobe system was developed to automate documenting the liquid-water-content uniformity in the test section. The stationary vertical bars were replaced by a set of nine 1.5-in.-(38.1-mm-) diameter rotating vertical bars that are set at specific intervals across the test section, allowing uniform ice buildup around the bar. After the bars are iced, a measuring unit is brought into the tunnel and is attached to each bar at a time (Figure 3). The measuring unit (of Figure 4), a linear variable differential transformer (LVDT), traverses the bar on a dual-shaft rail system with a ballscrew driven by a stepper motor. The traverse position is measured by a string potentiometer. An intelligent stepper motor indexer controls the traversing motion and starts and stops the data recording according to preprogrammed sequences. The operator in the tunnel uses a pushbutton control unit to select these sequences. The control unit also has a selector switch to indicate the number of the bar being measured. The facility data acquisition system records the ice accretion and the corresponding traverse position for each bar. It also provides real-time display plots and transfers the acquired data to a mainframe computer for postprocessing to create contour plots.

SYSTEM DESCRIPTION

Operating Procedure

The following steps are performed to operate the iceprobe system:

1. Stabilizing the tunnel: The desired tunnel parameters (temperature, air speed, spray duration, and spray bar air and water pressures) are selected and set.

2. Icing the bars: The spray bars are turned on to produce an icing cloud which accretes ice on the rotating bars.

3. Measuring the ice accretion: The icing measurement system is attached to each bar to measure and record ice accretion. Then the measurement system is moved to the next bar and the process repeated until all nine bars are measured.

4. Deicing the bars: The measurement system is removed from the tunnel, and the ice is scraped from the bars with plastic scrapers. Stubborn ice patches are removed with steam heat.

Ice Measuring Unit

The ice measuring unit (Figure 5) consists of a small, precision dual-shaft rail system that is mounted perpendicular to the bars and the traverse rails. It provides a sliding mechanism for two arms that have a cam follower mounted on the end. The cam followers ride along the bars as the device traverses the bar. The contact between the cam rollers and the bar is maintained by a spring attached to the arms, pulling them together. An LVDT measures the change in the distance between the arms, which is equal to twice the ice accretion because the measurement includes the ice accretion of the bar diameter.

The cam followers are left in the tunnel during the stabilization and icing so that they are cold when the bars are measured; warm cam followers tend to melt the ice, which could affect the measurement. Keeping the cam followers cold apparently has no effect on the ice accreted on the bar.

Traversing Motion System

An intelligent microstepping indexer and motor were selected as the central components of the control system (Figure 4). The indexer was programmed for several sequences selected by the operator using a control unit on the back of the measuring unit. These controls include power on/off, bar select, test, jog up, jog down, and stop. The control box also has lights to indicate data recording, motion, and power on.

The stepper motor has closed-loop encoder feedback and, in combination with the indexer, provides smooth motion as the ice measuring unit traverses the bar. When the operator pushes the test button, the indexer selects one of two sequences depending on the measuring probe location: at the bottom of travel or near the top. This selection allows alternating measuring from top to bottom for one bar and then from bottom to top for the next bar to reduce the overall measuring time.

DATA ACQUISITION AND REDUCTION

A distributed data system (4) provides the means of acquiring data for the measurement system. It is configured as a remote central VAX-based computer system and a facility computer system. The VAX-based system stores the data to generate the contour plots; the facility computer provides all the run-time processing for the calibration, online graphics display, and key interfaces between the test facility and the user. This system communicates with the central computer system, which is used for data storage and postprocessing.

The cloud uniformity is assessed by the accretion of ice on nine 1.5-in.-(38.1-mm-) diameter calibration bars placed in the tunnel test section. These bars are placed 9 in. (228.6 mm) apart with 18 in. (457.2 mm) between the end bars and the tunnel walls. A drive system rotates the bars, making a more even ice formation. The accretion uniformity is affected by tunnel boundary layer effects and water spray nozzle positions. Figure 6(a) shows the amount of ice on calibration bar nine. The center calibration bar was expected to have a more even accretion, the uniformity of which is represented in the flatness of the curve. The cumulative data for bars 1 to 9 are shown in Figure 6(b).

As described in Ice Measuring Unit, the diameter of the iced bars is measured by the LVDT; the vertical position for the location of the measurement is preprogrammed in the intelligent stepper system. Both the accretion and vertical displacement information are stored and transmitted to the facility and central computers through a DESnet network using the DECnet protocol.

For final data processing, the raw measurements are converted to relative liquid-water content normalized to the measurement at the center bar:

$$\frac{LWC(x,y)}{LWC_c} = \frac{D(x,y) - D_{bare}}{D_c - D_{bare}}$$

where: $LWC(x,y)$ = liquid-water content at each location

LWC_c = liquid-water content at the center of the test section

$D(x,y)$ = diameter of the iced bar at each location

D_c = diameter of the center iced bar

D_{bare} = diameter of the bare bar.

This equation was modified for the automated measurement system (5).

The central computer system uses the converted measurements to generate the contour plots. A representative contour plot map of the liquid-water-content (LWC) ratios for a cross section of the test section is presented in Figure 7. Hard copies of the raw data display pages and graphic plots can be obtained from a laser printer provided at the facility. This device communicates to the facility computer through an RS-232C interface.

COMPARISON OF MANUAL AND AUTOMATED MEASURING SYSTEMS

With the manual system, measurements of ice accretion were made every 2 in. (50.8 mm) along the bar. Errors were possible because the measurements were made manually by different people reading a tape measure to access nonuniform ice accretion on a round bar (Figure 2). Further, the tunnel was operated with only five of nine bars at a time, requiring two separate runs to obtain measurements across the whole test section. Using the iceprobe (automated) system, a relatively accurate measurement is obtainable and is recorded approximately every 0.5 in. (12.7 mm) along the bar without operator measuring errors. The manual system took approximately 2 hr to gather data for nine bars. The iceprobe system takes approximately 1 hr to obtain the data for all nine bar locations. Automation reduces the tunnel operating time and provides more opportunities to test different spray nozzle configurations. With

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the manual system, the data were recorded and plotted by hand; the iceprobe system provides automated data recording, calculations, plotting, and calibrations.

SYSTEM UNCERTAINTY ANALYSIS

The accuracy, or uncertainty, U is calculated from the cumulative sum of the system bias and precision errors which may effect the measurements. The general equations are

$$B_p = \pm\sqrt{\sum_i (b_i)^2}$$

$$S_p = \pm\sqrt{\sum_i (s_i)^2}$$

$$U_p = \pm(B_p + t_{95} S_p)$$

where: B_p = total bias error for the parameter to the ith measurand
S_p = total precision error for the parameter to the ith measurand
U_p = total uncertainty for each measured variable in percent of reading
t_{95} = 95th percentile point for the statistical parameter.

The methodology of the uncertainty analysis is given in Reference 6.

The error audit shows the sources to be those caused by the LVDT, signal conditioners, various mechanical apparatuses and, environmental effects. Table I presents the results of noted factors from the error audit. The quantitative value of each error source was obtained from the manufacturer's specification sheets (7 and 8) and from engineering analysis. The magnitude (in inches and millimeters) of each significant elemental error source was calculated and tabulated (Table II). The final uncertainty is represented in terms of ice accretion and traverse position.

The calculation for the accuracy of the ice accretion (LVDT) measurement is based on a consideration of four components. The first that may induce error is the LVDT. In this case, an unguided LVDT was selected. By design, the manufacturer's specifications suggest infinite resolution. The spring which tensions as the cam followers roll over the ice form is the second component. The third component is the error caused by the cam followers at the ice form contact area. Mathematical analysis shows that the error increases as the contact area arc length increases. The fourth component is data acquisition error. Three points were calculated to magnify the effect of the contact area. The elemental error values given in Table II are used to calculate the ice accretion measurement uncertainty as follows:

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Bias

$$B_{ice\ accretion} = \pm \sqrt{\sum_i (b_i)^2}$$

$$= \pm \sqrt{B_1^2}$$

$$= 0 \quad in. \ (0\ mm)$$

Precision

$$S_p = \pm \sqrt{\sum_i (s_i)^2}$$

$$S_{ice\ accretion} = \pm \sqrt{S_3^2 + S_5^2 + S_6^2 + S_7^2}$$

$$= \pm \sqrt{0.0001^2 + 0.0002^2 + 0.0002^2 + 0}$$

$$= \pm\ 0.0003\big|_{S_7 = 0^\circ} \quad in. \ (0.0075mm)$$

$$S_{ice\ accretion} = \pm \sqrt{S_3^2 + S_5^2 + S_6^2 + S_7^2}$$

$$= \pm \sqrt{0.0001^2 + 0.0002^2 + 0.0002^2 + 0.0153}$$

$$= \pm\ 0.0153\big|_{S_7 = 1^\circ} \quad in. \ (0.38210\ mm)$$

$$S_{ice\ accretion} = \pm \sqrt{S_3^2 + S_5^2 + S_6^2 + S_7^2}$$

$$= \pm \sqrt{0.0001^2 + 0.0002^2 + 0.0002^2 + 0.1527}$$

$$= \pm\ 0.1527\big|_{S_7 = 10^\circ} \quad in. \ (3.8175\ mm)$$

Total

$$U_{ice\ accretion} = \pm (B_{ice\ accretion} + t_{95}\ S_{ice\ accretion})$$

$$= \pm\ 0 + 2 \times 0.0003$$

$$= \pm\ 0.0006\big|_{S_7 = 0^\circ} \quad in. \ (0.015\ mm)$$

$$U_{ice\ accretion} = \pm (B_{ice\ accretion} + t_{95}\ S_{ice\ accretion})$$

$$= \pm 0 + 2 \times 0.0153$$

$$= \pm 0.0306|_{S_7 = 1°}\ in.\ (0.7642\ mm)$$

$$U_{ice\ accretion} = \pm (B_{ice\ accretion} + t_{95}\ S_{ice\ accretion})$$

$$= \pm 0 + 2 \times 0.1527$$

$$= \pm 0.3057|_{S_7 = 10°}\ in.\ (7.6425\ mm)$$

The calculation of the accuracy of the traverse measurement is based on a consideration of two components. The accuracy of the string potentiometer can minimize this contribution to error. In this case, a linear absolute string potentiometer was selected. The manufacturer's specifications suggest infinite resolution. The second contributor is the glide system. The traverse system measurement uncertainty is calculated as

Bias

$$B_{traverse\ position} = \pm\sqrt{\sum_i (b_i)^2}$$

$$= \pm\sqrt{B_1^2}$$

$$= 0\ in.\ (0\ mm)$$

Precision

$$S_p = \pm\sqrt{\sum_i (s_i)^2}$$

$$S_{traverse\ position} = \pm\sqrt{S_8^2 + S_9^2 + S_{11}^2 + S_{12}^2}$$

$$= \pm\sqrt{0.08^2 + 0.08^2 + 0.002^2 + 0.002^2}$$

$$= \pm 0.11315\ in.\ (2.829\ mm)$$

Total

$$U_{traverse\ position} = \pm (B_{traverse\ position} + t_{95}\ S_{traverse\ position})$$

$$= \pm 0 + 2 \times 0.11315$$

$$= \pm 0.2263\ in.\ (5.658\ mm)$$

The best-case analysis of the ice accretion uncertainty was calculated to be ± 0.006 in. (0.015 mm), and the traverse position (string potentiometer) was calculated to be ± 0.2263 in. (5.658 mm). Table III shows the overall system uncertainty. These uncertainties were calculated by using the Abernethy uncertainty method. The limiting factors for error originating from mechanical assembly and coupling dominate the error in the ice accretion (Reference 6). The transducer accuracy dominates the error of the traverse system.

CONCLUSION

The development and installation of an automated rotating bar measurement system have led to improvements in the operation of the Icing Research Tunnel. Use of the iceprobe system to calibrate the tunnel has made possible a 50-percent reduction in calibration run time. In the choice of a device to measure ice accretion on the rotating bars, the most critical consideration was given to operating accurately and reliably in the cold environment: the linear variable differential transformer can operate in temperatures ranging from −50 to +70 °C and can measure thousandths of inches (hundredths of millimeters) of change whereas the manual system used a flexible tape to measure to the nearest 0.125 in. (3.125 mm). The number of data points was increased as was the accuracy in obtaining them. The data acquisition system provides online graphics plots and gives immediate feedback as to the effect of the spray nozzle locations in the spray bars. Because contour plots can be generated within minutes of test completion., they can be used as baseline plots of the cloud uniformity. Thus, it is possible to document the characteristics of various nozzle sprays.

REFERENCES

1. Reinman, J., and Shaw, R., "NASA's Program on Icing Research and Technology," NASA TM–101989, May 1989.

2. "An International Historic Mechanical Engineering Landmark: Icing Research Tunnel," NASA B-87-0011, NASA Lewis Research Center, May 1987.

3. Soeder, R., and Andracchio, C., "NASA Lewis Icing Research Tunnel User Manual," NASA TM-102319, June 1990.

4. Fronek, D., Setter, R., Blumenthal, P., and Smalley, R., "A Distributed Data Acquisition System for Aeronautics Test Facilities, NASA TM-88961, May 1987.

5. Ide, R.F., "Liquid Water Content and Droplet Size Calibration of the NASA Lewis Research Tunnel," NASA TM-102447, Jan. 1990.

6. Abernethy, R.B., and Thomson, T.W., Measurement Uncertainty Handbook, Instrument Society of America, Research Triangle Park, NC, 1980.

7. "ACT1000 Displacement Transducer Specification & Calibration Sheet," RDP-Electosense, Pottstown, PA, March 1991.

8. "Linear Motion Transducer Model PSA-80A(LT) Specification Sheet," Magnetec, Simi Valley, CA, Jan. 1992.

TABLE I.—ERROR SOURCE AUDIT

Error Source	Code
Unguided linear variable differential transformer (LVDT)	S_1, S_2, S_3
Spring	S_4
Signal conditioners	S_5, S_6
Cam followers	S_7^a
String potentiometer	S_8, S_9, S_{10}
Glide system	S_{11}, S_{12}
ESCORT D data acquisition system	B_1, S_{13}

^{a}This accuracy is based on three arc length calculations.

TABLE II.—QUANTITATIVE ERRORS

Error code	Percent full scale	Range		Comments
		in.	mm	
S_1		0	0	Unguided LVDT repeatability error
S_2		0	0	Unguided LVDT hysteresis error
S_3	0.01	0.0001	0.0025	Unguided LVDT zero temperature error
S_4		Negligible	Negligible	Spring
S_5	0.002	0.0002	0.005	Signal conditioner zero temperature error
S_6	0.002	0.0002	0.005	Signal conditioner span temperature error
S_7^a		0	0	Cam followers (0°)
S_7^a		0.0153	0.38175	Cam followers (1°)
S_7^a		0.1527	3.8175	Cam followers (10°)
S_8	0.01	0.080	2	String potentiometer repeatability error
S_9	0.01	0.080	2	String potentiometer hysteresis error
S_{10}		0	0	String potentiometer temperature error
S_{11}		0.002	.05	Glide system repeatability
S_{12}		0.002	.05	Glide system hysteresis
B_1, S_{13}		Negligible	Negligible	ESCORT D

^{a}This accuracy is based on three arc length calculations.

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TABLE III.—ICEPROBE SYSTEM UNCERTAINTY

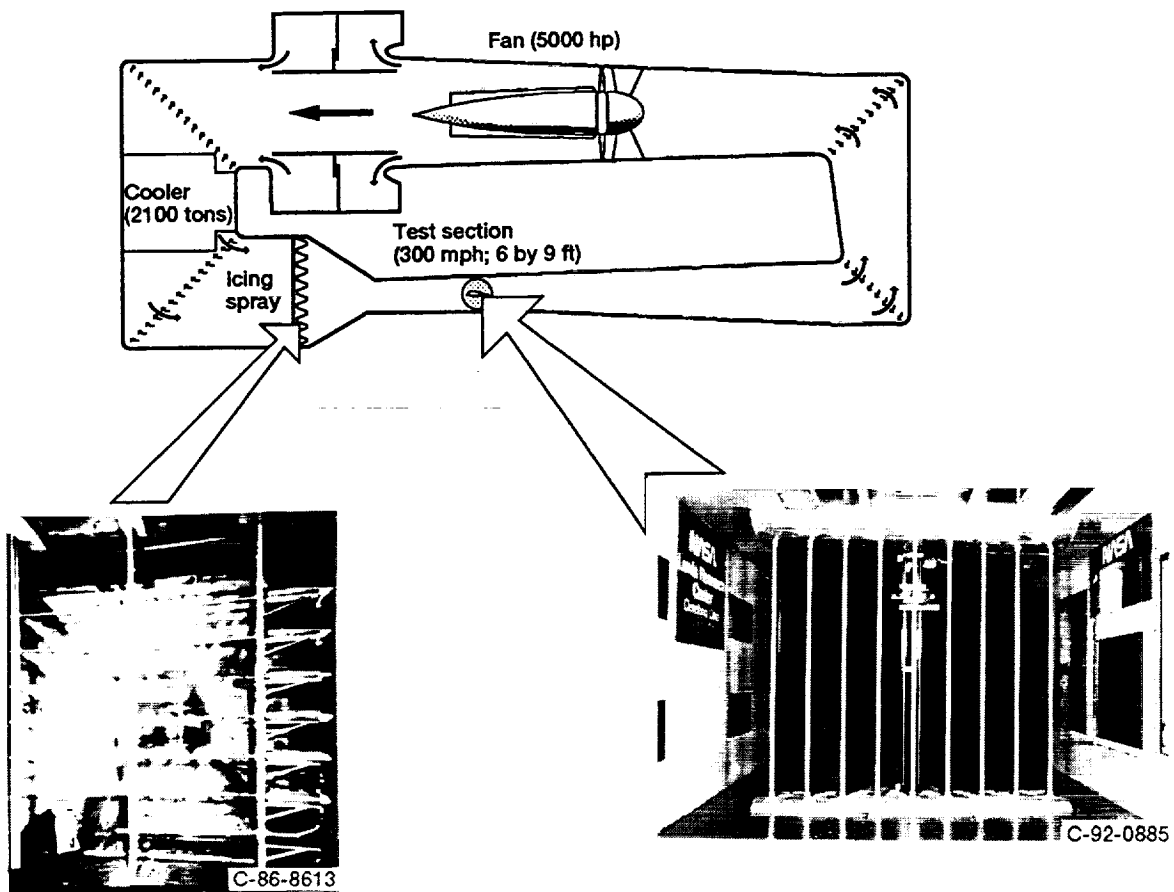| Total uncertainty, U	Range, in.	Range, mm
$U_{ice\ accretion}$ where $S_7 = 0°$	±0.0006	±-0.015
$U_{ice\ accretion}$ where $S_7 = 1°$	±0.0306	±0.7642
$U_{ice\ accretion}$ where $S_7 = 10°$	±0.3057	±7.6425
$U_{traverse\ position}$	±0.2263	±5.658

Figure 1.—Icing Research Wind Tunnel spray bar and calibration bar locations.

Figure 2.—Manual ice accretion measurement.

Figure 3.—Iceprobe system and control unit.
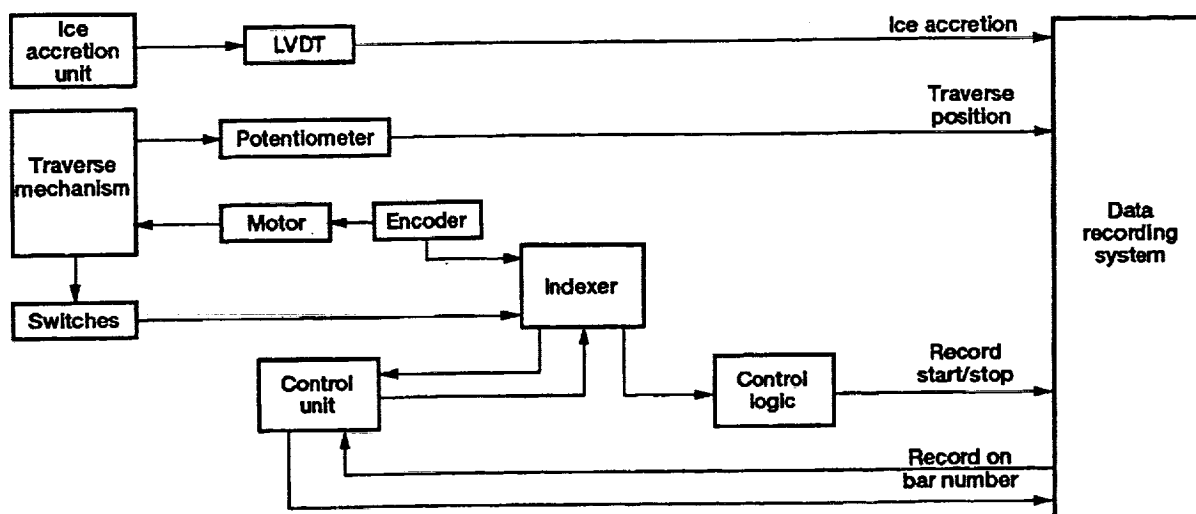
Figure 4.—Measurement and control system.
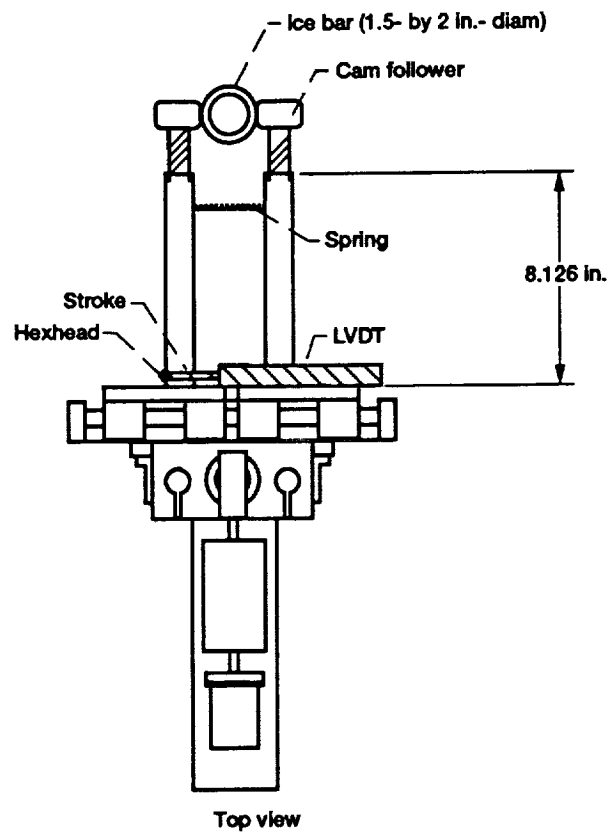
Top view
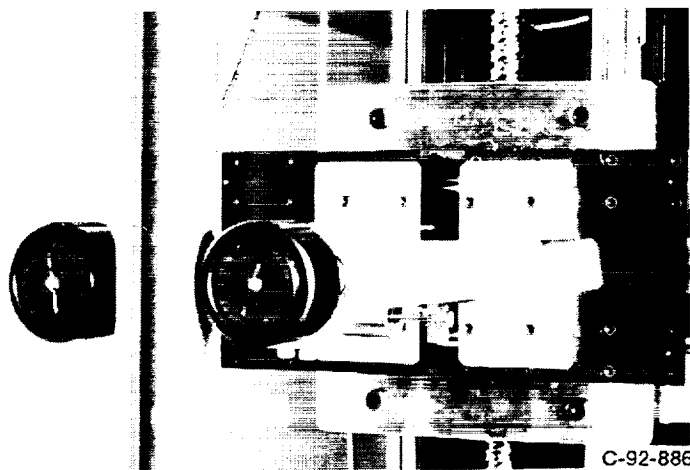
Front view

Figure 5.—Iceprobe measurement unit.

(a) Bar 9.

(b) Cumulative data for bars 1 to 9.
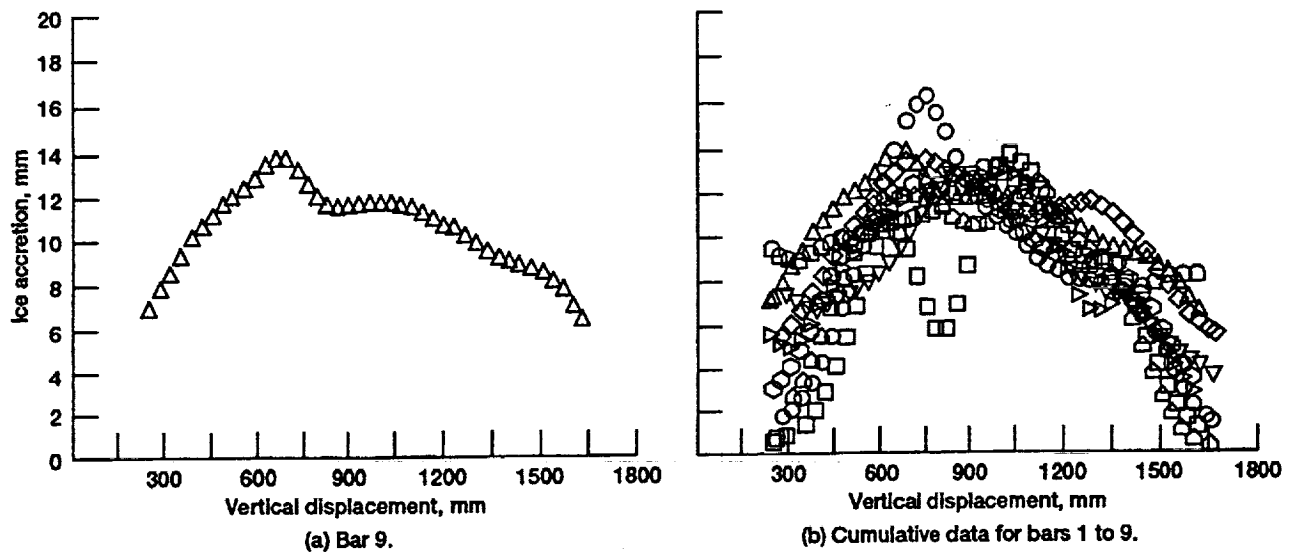
Figure 6.—Data profiles for calibration bars.

Test section width, in.
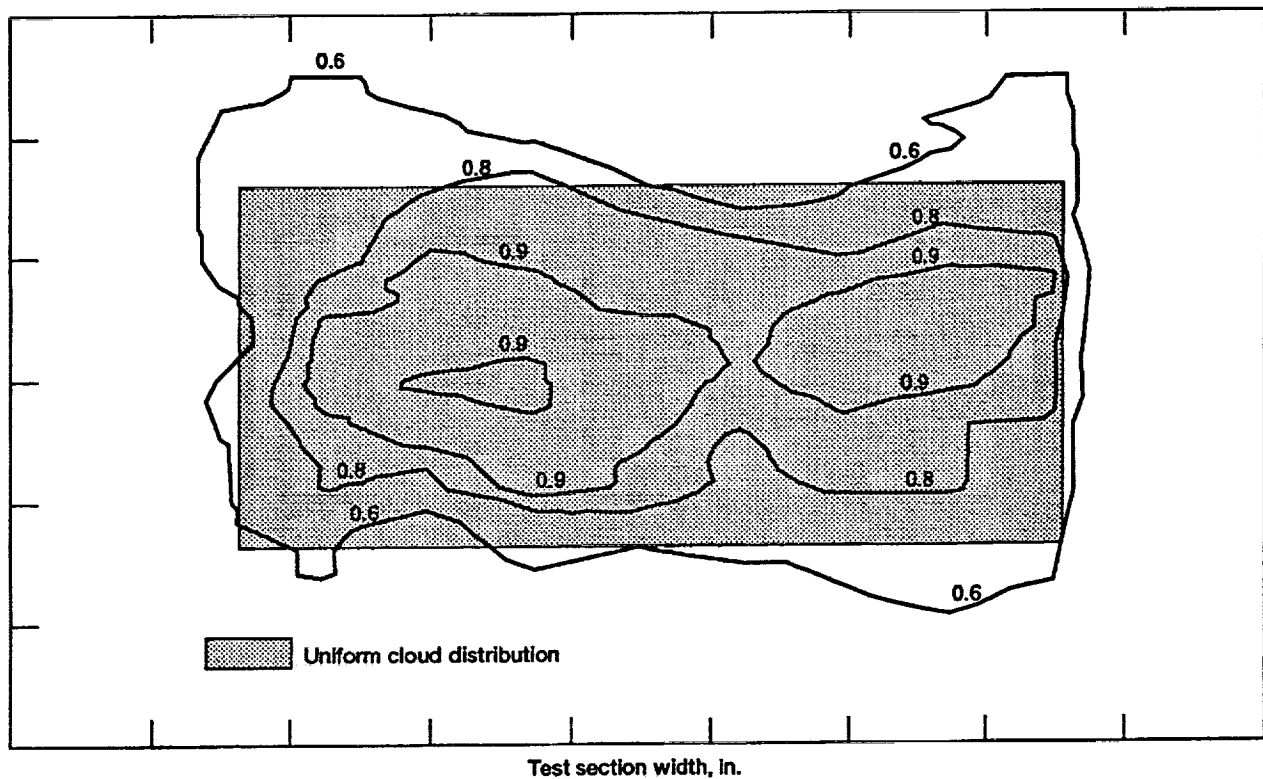
Figure 7.—Contour plot of data for bars 1 to 9. Contours are liquid water content (LWC) ratios: ratio of local diameter to bare bar diameter/center diameter to bare bar diameter.

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13. ABSTRACT (Maximum 200 words)

In order to measure icing patterns across a test section of the Icing Research Tunnel, an automated rotating bar measurement system was developed at the NASA Lewis Research Center. In comparison with the previously used manual measurement system, this system provides a number of improvements: increased accuracy and repeatability, increased number of data points, reduced tunnel operating time, and improved documentation. The automated system uses a linear variable differential transformer (LVDT) to measure ice accretion. This instrument is driven along the bar by means of an intelligent stepper motor which also controls data recording. This paper describes the rotating bar calibration measurement system.

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